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Prediction of average annual surface temperature for both flexible and rigid pavements

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ABSTRACT

The surface temperature of pavements is a critical attribute during pavement design. Surface temperature must be measured at locations of interest based on time-consuming field tests. The key idea of this study is to develop a temperature profile model to predict the surface temperature of flexible and rigid pavements based on weather parameters. Determination of surface temperature with traditional techniques and sensors are replaced by a newly developed method. The method includes the development of a regression model to predict the average annual surface temperature based on weather parameters such as ambient air temperature, relative humidity, wind speed, and precipitation. Detailed information about temperature and other parameters are extracted from the Federal Highway Administration's (FHWA) Long Term Pavement Performance (LTPP) online database. The study was conducted on 61 pavement sections in the state of Alabama for a 10-year period. The developed model would predict the average annual surface temperature based on the known weather parameters. The predicted surface temperature model for asphalt pavements was very reliable and can be utilized while designing a pavement. The study was also conducted on seven rigid pavement sections in Alabama to predict their surface temperature, in which a successful model was developed. The outcome of this study would help the transportation agencies by saving time and effort invested in expensive field tests to measure the surface temperature of pavements.

1 Introduction

Temperature variations affect both rigid and flexible pavements. Though pavements primarily consist of crushed stone aggregates, which are not reactive to temperature, the binder used to bind the aggregates is more dependent on temperature. One of the most important properties of asphalt binder is viscosity, which is dependent on temperature. Measuring the surface temperature of pavements by utilizing sensors on a regular basis would be time-consuming and uneconomical. To overcome this issue, the Federal Highway Administration (FHWA) decided to install weather stations to continuously monitor the weather conditions at different locations in the USA and Canada. Monitoring and recording data is maintained

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and managed by the Long-Term Pavement Performance (LTPP) database under the Strategic Highway Research Program (SHRP). The recorded data is saved under LTPP National Information Management System, which includes information on environment, traffic, materials, maintenance, and up to date rehabilitation details of pavements. An instrumentation system called Weather Station installed at different locations records all the climatic parameters like air temperature, wind speed, relative humidity, precipitation, and solar radiation. The surface temperature of a pavement is measured using the infrared temperature sensors equipped with the Falling Weight Deflectometer (FWD) devices. Surface temperature is an important factor while designing a pavement structure for three major factors: (1) Asphalt is a visco-elastic material and its properties change with temperature, (2) Expansion and contraction in both PCC and AC layer due to change in temperature can lead to top-down thermal cracking, which would decrease the pavement life, and (3) Transverse top-down cracks may develop in the hot mix asphalt (HMA) layer due to extreme decrease in temperature in a single day or weeks. The surface temperature is traditionally measured by core-drilling method in the field, which is an expensive procedure and requires a lot of manpower. Also, failure to proper refill of the core drilled spots would induce structural failure of pavement with intrusion of rain water into the asphalt layer. The traditional core-cutting method is replaced by sensors (figure 1) in recent days with technology developments, which avoids the physical damage caused to pavements. However, considerable time is consumed to reach various locations to measure surface temperature with sensors.

Fig. 1 – Surface Patrol sensors for measuring real-time pavement surface temperature

2 Literature Review

Significant amount of research on temperature profile modelling has been carried out since 1960s by various researchers [1, 2, 3]. Khadrawi et al. [4] described the effect of temperature on flexible pavements in the study, which mentioned that the surface temperature of pavements is dependent on ambient air temperature, wind speed, and other parameters. Also, the study revealed the importance of predicting the pavement temperature at any required depth. A heat transfer model was developed to monitor thermal behaviour of HMA, which can predict the pavement temperature at any depth, using the surface and ambient air temperature, solar radiation, and thermal properties of asphalt binder. The limitation with the developed model was the assumption that the depth of HMA to be infinite, while other typical thermal properties were not given much importance.

Wang [5] was interested in predicting temperature profiles for a multi-layered pavement system by developing an algorithm to predict one dimensional temperature profile, using the properties of HMA, pavement depth, and surface temperature. Even though the predicted values were validated with the measured values between 1964 and 1965, the model is not effective to present day asphalt mixture properties. In addition, the validated values did not match the actual values at depths greater than 0.15 meters. The importance of the pavement surface temperature and its relationship with failures of flexible and rigid pavements were considered as the main objective in many research studies [6 – 9].

Yavuzturk developed a two-dimensional finite difference model to determine temperature at an hourly basis, as it is completed by LTPP in recent days [10]. This model related most climatic factors such as ambient air temperature, solar radiation, pavement orientation, and geometry in addition to thermal properties of pavement materials. The model was successful but very complex to utilize for the practicing engineers since it included many variables. Nonetheless, this model established a clear path to forthcoming researchers to develop a simpler model to predict pavement temperature profiles.

Diefenderfer [11] set up an instrumentation station in Virginia, named Virginia Smart Road (VSR), to develop two simple statistical models to predict the maximum and minimum temperature at any depth of the pavement. Diefenderfer Statistical Model (DSM) was successful with its objective and results, but the model needed installation of the instrumentation station at every required pavement location to estimate the temperature profiles using DSM model.

Islam [12] evaluated the structural capacity of Interstate 40 (I-40) pavement sections in New Mexico (NM), using the DSM and SHRP LTPP models. The pavement temperature at a depth of 263 mm was estimated using the existing SHRP LTPP models. The values were not appropriate nor consistent because of the difference in the HMA mixture design and geometry of NM pavements compared to Virginia pavement properties. Islam also installed an instrumentation section with the help of the National Center for Asphalt Technology (NCAT) of Auburn University and NMDOT (New Mexico Department of Transportation), on Interstate 40 eastbound lane. The section had four layers with detailed information about each layer and their properties such as layers thicknesses, type of asphalt concrete used in mix and asphalt binder grade. The installed instruments in the section was well equipped with forty sensors to measure the vertical stresses, horizontal strain, air temperature, solar radiation, pavement temperatures and moisture. Linear Regression analysis was utilized to develop the profile models and was validated using ANOVA test. To predict the temperature of pavement at any depth, an equation was derived, which included parameters such as surface temperature of pavements, solar radiation and the respective depth of pavement at which temperature is to be determined. The equation developed to predict the surface temperature of pavement was

$$x_{avg} = 1.136*a_{avg} + 4.956$$

where, x_{avg} is the average surface temperature (in ^{o}C) and a_{avg} is the average air temperature (in ^{o}C)

One of the important limitations with the developed model was that the predicted surface temperature considered the ambient air temperature alone as a factor affecting pavement' surface temperature. However, there is a high possibility for the surface temperature to be influenced by other weather parameters such as humidity, precipitation, and wind speed. The developed model from this study can help in pavement designing procedures by providing an easy, quick, and cost-effective alternative to predict pavement surface temperature rather than the field-testing method. The model could be added as an attribute in any pavement designing software for easy accessibility that anyone can predict the approximate value of pavement surface temperature by imputing the weather parameters, which can be easily accessed from readily available weather stations near the intended pavement structure.

3 Objective

The objective of this study is to develop a temperature profile model to predict the average annual surface temperature of both hot mix asphalt (HMA) and rigid pavements in the state of Alabama. The developed models were based on weather parameters such as air temperature, humidity, precipitation, solar radiation, and wind speed.

4 Data Collection

The climatic parameters required were collected from the LTPP online database. The Long-Term Pavement Performance (LTPP) is the largest pavement performance research program, initiated in 1987 as a part of the Strategic Highway Research Program (SHRP). Under the sponsorship of the Federal Highway Administration (FHWA) and with the cooperation of the American Association of State Highway and Transportation Officials (AASHTO), the Transportation Research Board (TRB) of the National Research Council undertook a Strategic Transportation Research Study (STRS) of the Nation's highway and bridge infrastructure systems. Based on this study, a report was published in 1984 as a TRB special report 202, "America's Highways, Accelerating the Search for Innovation". The LTPP program was among the six strategic research areas recommended by the TRB report [13]. Location of LTPP Alabama sections considered for the study are shown in figure 2.

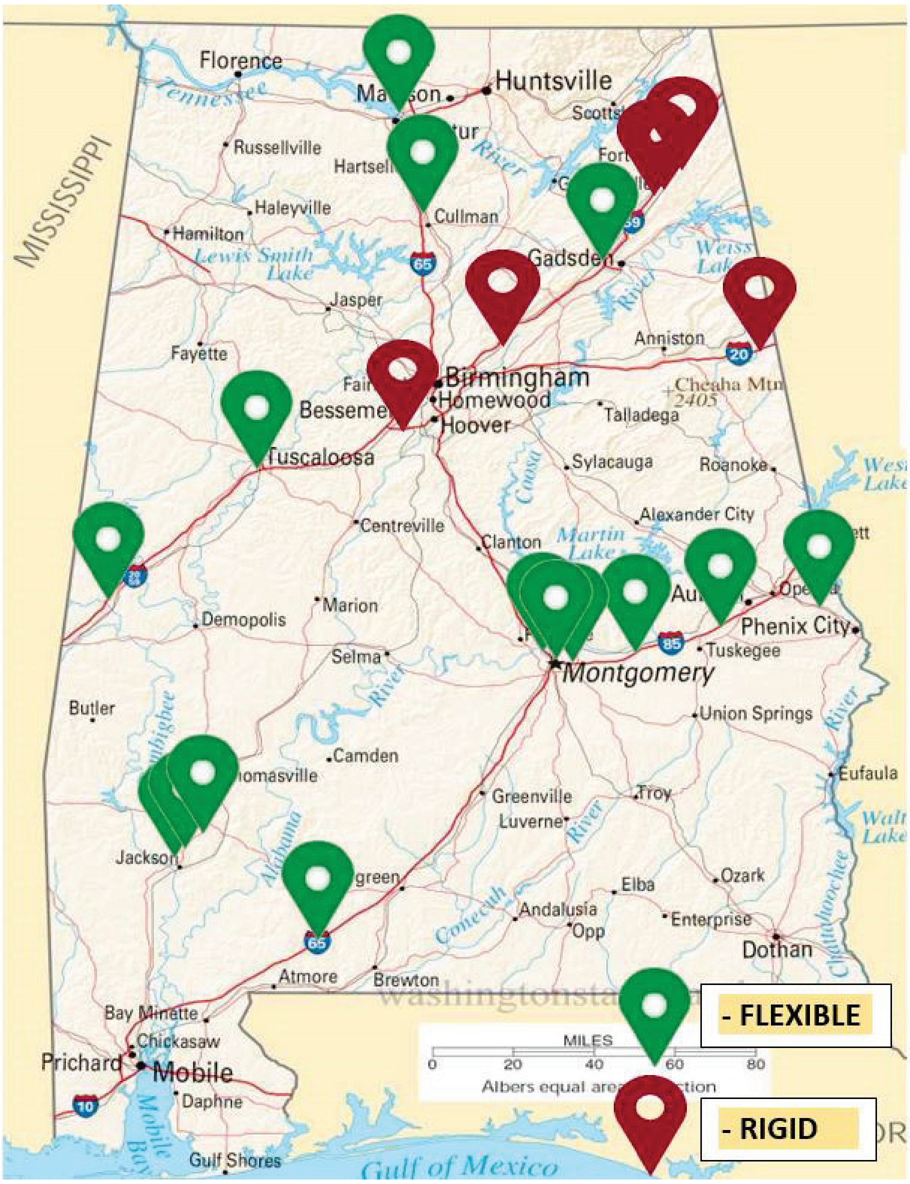


Fig. 2 – Locations of flexible and rigid pavement sections considered in Alabama.

The instrumentation system installed at all sites recorded climatic parameters such as air temperature, wind speed, humidity, precipitation, and solar radiation, followed by updating the online database. The surface temperature is measured using Falling Weight Deflectometer sensors at the beginning and at the end of each section. Every LTPP section is 153 meters in length. The database is maintained as an open source (free to access), which can be accessed by whoever needs the data. The database is updated periodically to ensure the accuracy of data available in the database. The map available in the database provides a clear idea of the location of the installed section. A sample of the data collected is shown in table 1.

Table 1 – Weather parameters obtained from LTPP database for the SHRP section 0101

Year	Air Temperature, Ta (ºC)	Wind Speed, w (m/sec)	Relative Humidity, RH (%)	Surface Temperature, Ts(ºC)
1997	19.08	2.7	70.0	22.66
2000	30.23	2.6	64.5	44.46
2002	26.37	2.6	66.5	36.55
2004	12.58	2.7	66.5	11.20

To develop the pavement surface temperature model, 61 flexible pavement sections and 7 rigid pavement sections were considered. Data was collected over a 10-year period from 1995 to 2005 generating 171 and 19 data points for flexible and rigid pavements, respectively.

5 Data Analysis And Model Development

A huge amount of climatic data was collected, including air temperature (Ta), surface temperature (Ts), wind speed (w), precipitation (P), and relative humidity (RH) for the state of Alabama. The number of sections considered for the study are 61 and 7 for HMA and rigid pavements, respectively. The surface temperature prediction models were developed from the collected data via linear regression analysis. The overall average annual surface temperature for the entire state of Alabama ranged in between 2 °C and 52 °C during various seasons. Approximately, 80% of the collected data points were used to develop the prediction statistical models while the remaining 20% were left for model validation afterwards. Therefore, 136 out of 171 data points are considered for the regression analysis of the pavement surface temperature of flexible pavement sections. All collected weather parameters were considered into account while developing the prediction regression model as presented in (equation 1). The statistical results from the regression analysis conducted on flexible pavement sections are shown (table 2).

Table 2 – Results from regression analysis conducted for 61 HMA sections

Regression Statistics	
Multiple R	0.923287
R Square	0.852460
Adjusted R Square	0.847955
Standard Error	4.572426
Observations	136

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	15824.41958	3956.1049	189.223241	2.081E-53
Residual	131	2738.827101	20.9070771		
Total	135	18563.24668			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	19.031479	10.2433	1.8579	0.0654	-1.2322	39.2952	-1.2322	39.2952
Ta	1.582541	0.0705	22.4338	0.0000	1.4430	1.7221	1.4430	1.7221
P	-0.143224	1.8908	-0.0757	0.9397	-3.8836	3.5972	-3.8836	3.5972
RH	-0.223764	0.1268	-1.7640	0.0801	-0.4747	0.0272	-0.4747	0.0272
WS	-2.694449	1.3137	-2.0510	0.0423	-5.2933	-0.0956	-5.2933	-0.0956

By observing the results, the values of Standard Error and R Square proves that the model is less significant to errors. The developed average annual surface temperature prediction model for flexible pavement sections is as follows:

Average Annual Surface Temperature,

$$Ts = 1.582541*(Ta) - 0.14322*(P) - 0.22376*(RH) - 2.69445*(WS) + 19.03148 \tag{1}$$

where, Ts = average annual surface temperature of pavement (°C)
Ta = ambient air temperature (°C)
WS = average annual wind speed (m/s)
P = annual precipitation (m)
RH = relative humidity (%)

Based on the developed model, the average annual surface temperature (Ts) can be estimated. The measured average annual surface temperature is compared to the predicted Ts as shown in figure 3.

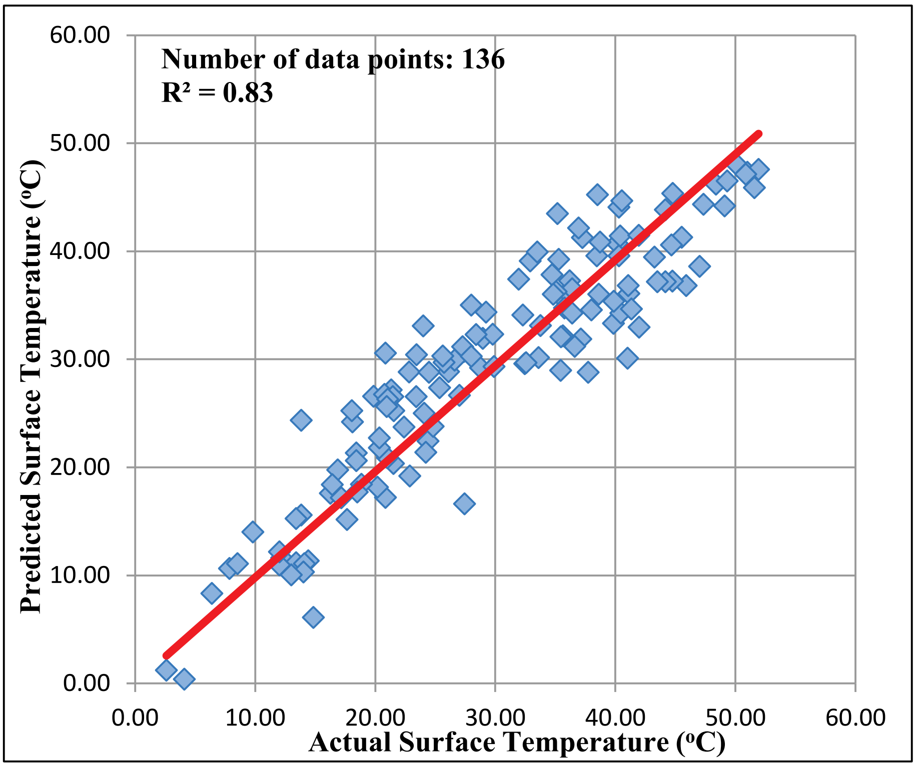


Fig. 3 –Developed model to predict surface temperature of flexible pavements in Alabama.

By observing the plot with R2 value of 0.83, it can be concluded that the predicted surface temperature is very well correlated to the actual surface temperature. In order to classify the developed model as successful, the model must be validated which is shown in the following section of this paper.

Similar to flexible pavements, regression analysis was conducted for rigid pavements utilizing 15 data points of 6 sections as shown in table 3.Based on the results of regression analysis and coefficients, a model is developed to predict the average annual surface temperature of rigid pavements in Alabama (equation 2). Based on the developed model, the predicted surface temperature is compared with the actual measured surface temperature as shown in (figure 4).

Average Annual Surface Temperature,

$$Ts = 1.457465*(Ta) - 12.0261*(WS) - 0.57978*(RH) - 0.70796*(P) + 67.55235 \tag{2}$$

where, Ts = average annual surface temperature of pavement (°C)
Ta = ambient air temperature (°C)
WS = average annual wind speed (m/s)
P = annual precipitation (m)
RH = relative humidity (%)

By observing the plot with R^2 value of 0.94, it can be concluded that the predicted surface temperature is very well correlated to the actual surface temperature. In order to classify the developed model as successful, the model must be validated which is shown in the following section of this paper.

Table 3 – Results from regression analysis conducted for 6 rigid pavement sections

Regression Statistics	
Multiple R	0.96912839
R Square	0.93920983
Adjusted R Square	0.91489376
Standard Error	3.4225478
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	1809.7905	452.44762	38.625069	4.73E-06
Residual	10	117.13833	11.713833		
Total	14	1926.9288			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	67.552345	37.7353	1.7902	0.1037	-16.527	151.63	-16.52	151.63
P	-0.707964	1.5747	-0.4496	0.6626	-4.2165	2.8006	-4.2165	2.8006
RH	-0.579779	0.483	-1.2004	0.2576	-1.6559	0.4964	-1.6559	0.4964
WS	-12.026091	5.9458	-2.0226	0.0707	-25.274	1.2221	-25.274	1.2221
Ta	1.457465	0.1223	11.9166	0	1.185	1.73	1.185	1.73

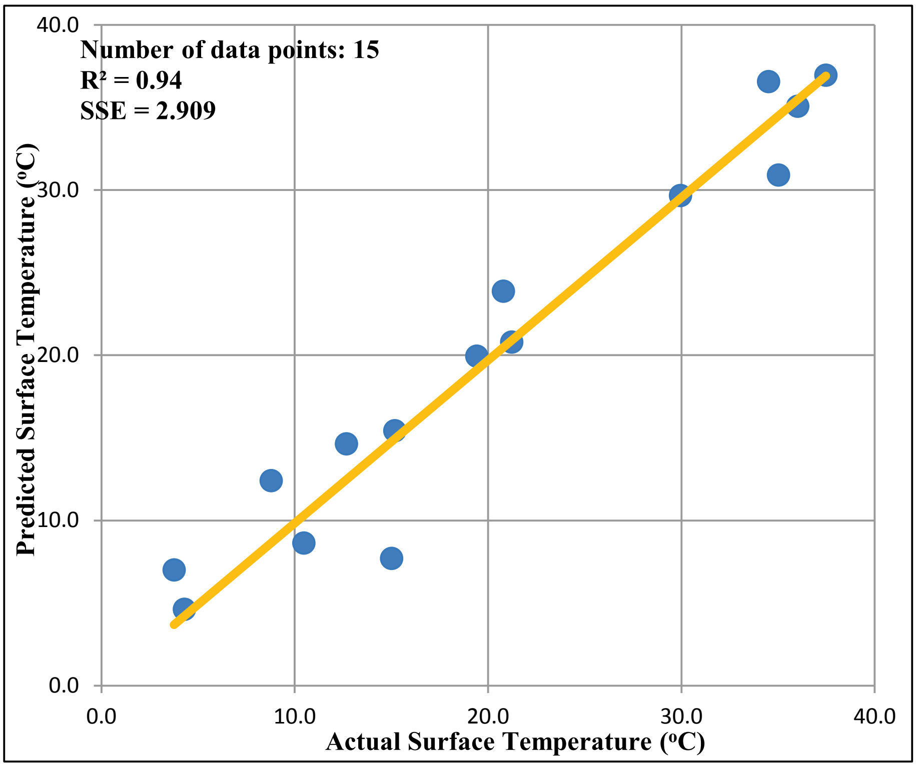
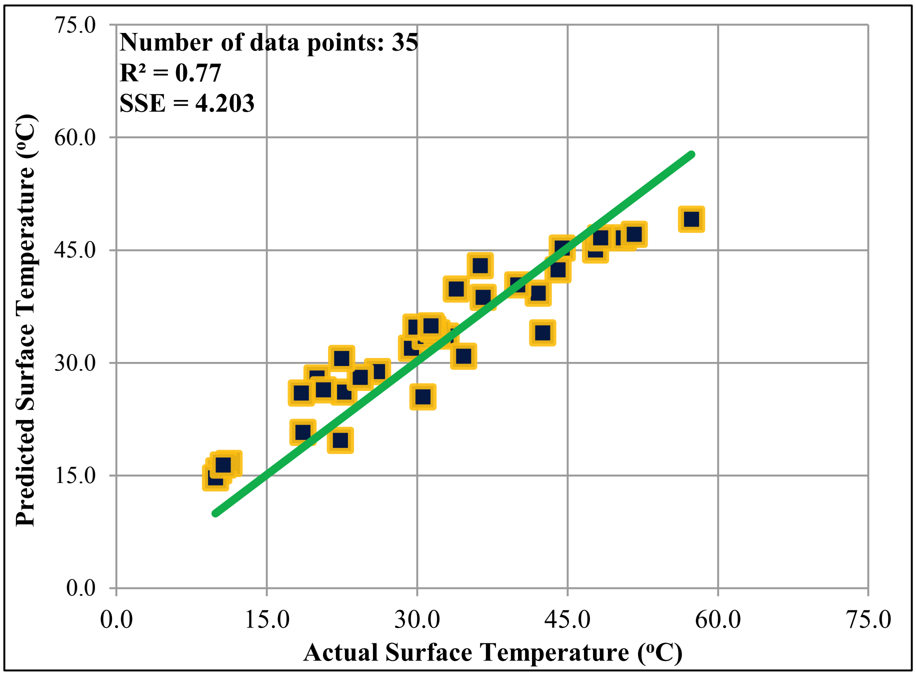


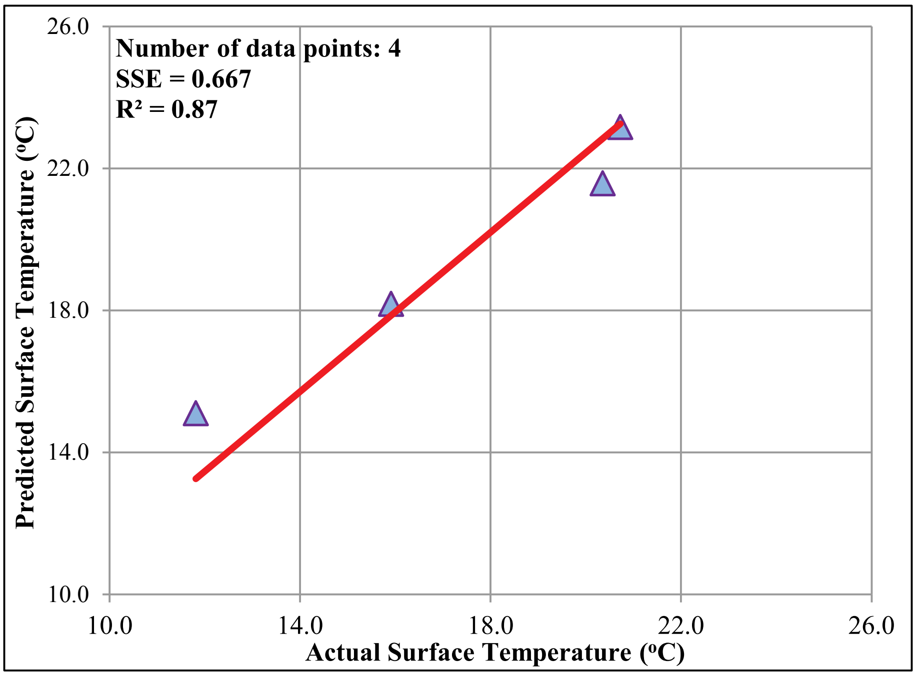
Fig. 4 – Developed model to predict surface temperature of rigid pavements in Alabama.

6 Data Analysis and Model Validation

To validate the established models, pavement sections excluded from regression analysis during model development were utilized at this stage. For example, to validate the developed models, 35 and 4 data points were excluded from regression analysis for flexible and rigid pavements, respectively. Validation method selected in this study included a plot between predicted and actual surface temperatures of the pavement sections that were not involved in the model development stage (figures 5 a, b).



(a)



(b)

Fig. 5 – Developed model validation: a) Flexible pavements, b) Rigid pavements.

By observing figures 5a & b, the relationship between predicted and actual average annual surface temperatures was noticed to be accurately predicting the remaining validation sections, which were not included during model development. The determination coefficient, R2 values illustrates the level of reliability of the developed models. Hence, the developed models can be utilized during pavement design instead of conducting an expensive field test. With the development of reliable models to predict the average annual surface temperature, the objective of this study is considered to be well accomplished.

7 Conclusion

The study developed statistical models based on the collected data by the automated weather stations, which avoids common manipulation errors that occurs using manual calculations. The developed model for predicting the average annual surface temperature can be utilized to predict surface temperatures of both flexible and rigid pavements for the state of Alabama. The predicted models are fairly reliable and can be utilized while designing the pavements in future without any expensive and time-consuming field tests. However, it should be noted that the developed model is limited to report the average annual surface temperature of pavement sections. Prediction of pavement temperature at any instant of time at various depths from the surface are to be investigated in further studies.

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